Mon. Not. R. Astron. Soc. **336,** 1021–1029 (2002)

Probing the dark ages with metal absorption lines

S. Peng Oh⋆
Theoretical Astrophysics, Mail Code 130-33, Caltech, Pasadena, CA 91125, USA

Accepted 2002 July 5. Received 2002 June 20; in original form 2002 February 8

ABSTRACT

Recent observations of high-redshift quasars at $z \sim 6$ have finally revealed complete Gunn–Peterson absorption. However, this at best constrains the volume-weighted and mass-weighted neutral fractions to be $x_{\rm HI}^{\rm V} \geqslant 10^{-3}$ and $x_{\rm HI}^{\rm M} \geqslant 10^{-2}$ respectively; stronger constraints are not possible because of the high optical depth for hydrogen Lyman transitions. Here I suggest certain metal lines as tracers of the hydrogen neutral fraction. These lines should cause unsaturated absorption when the intergalactic medium is almost fully neutral, if it is polluted to metallicities $Z \sim 10^{-3.5}$–$10^{-2.5}$ $\mathrm{Z}_{\odot}$. Such a minimal level of metal pollution is inevitable in the middle to late stages of reionization unless quasars rather than stars are the dominant source of ionizing photons. The O I line at 1302 Å is particularly promising: the O I and H ionization potentials are almost identical, and O I should be in very tight charge exchange equilibrium with H. The Si II 1260 Å transition might also be observable. At high redshift, overdense regions are the first to be polluted to high metallicity but the last to remain permanently ionized, as a result of the short recombination times. Such regions should produce a fluctuating O I and Si II forest, which, if observed, would indicate large quantities of neutral hydrogen. The O I forest may already be detectable in the Sloan Digital Sky Survey $z = 6.28$ quasar. If seen in future high-redshift quasars, the O I and Si II forests will probe the topology of reionization and metal pollution in the early Universe. If, in addition, the H I optical depth can be measured from the damping wing of a high-redshift γ-ray burst, they will yield a very robust measure of the metallicity of the high-redshift Universe.

Key words: galaxies: high-redshift – intergalactic medium – quasars: absorption lines – cosmology: theory – early Universe.

1 INTRODUCTION

Recent spectroscopic observations (Becker et al. 2001; Djorgovski et al. 2001; Pentericci et al. 2002) of high-redshift quasars discovered by the Sloan Digital Sky Survey (SDSS; Fan et al. 2000, 2001a) have revealed long gaps in the spectra consistent with zero transmitted flux. This long-awaited detection of the Gunn–Peterson effect may herald the observational discovery of the reionization epoch. However, the high oscillator strength of the hydrogen Lyα transition means that complete Gunn–Peterson absorption is expected even for a highly ionized intergalactic medium (IGM). The strongest constraint comes from the Lyβ absorption trough, because of the weaker (by ∼5) oscillator strength of Lyβ. From the $z = 6.28$ quasar observed by Becker et al. (2001) and Fan et al. (2001b), it was concluded that, at $z \sim 6$, the lower limits on the mass-weighted and volume-weighted neutral hydrogen fraction are $x_{\rm HI}^{\rm M} > 10^{-2}$ and $x_{\rm HI}^{\rm V} > 10^{-3}$ respectively, larger by almost two orders of magnitude than those at $z \sim 4$. Studies interpreting the observations conclude that the observed absorption troughs are consistent with the tail end of reionization or post-overlap phase after individual H II regions have merged (Barkana 2001; Fan et al. 2001b). However, owing to the rapid or phase-change-like nature of reionization in standard scenarios (Gnedin 2000; Razoumov et al. 2002), the 'dark ages' or pre-overlap phase, when a substantial fraction of the hydrogen in the Universe was neutral, is likely not far off. The spectra of the $z = 6.28$ quasar suggests a very rapid evolution in the effective optical depth and thus the ionizing radiation field and effective neutral fraction (Fan et al. 2001b). This implies that a slightly higher-redshift quasar may indeed lie within the pre-overlap era.

Unfortunately, even if such a quasar is discovered, we may not learn anything new about the pre-reionization epoch. The hydrogen Lyman-series absorption trough saturates fully for a neutral hydrogen fraction at mean density $x_{\rm HI} \sim 10^{-4}$; because the transmitted flux declines exponentially with increasing neutral fraction, we do not have the power to distinguish between an almost fully neutral IGM and one with only a tiny neutral fraction. As the IGM becomes almost fully neutral, we might observe the red damping wing of the Gunn–Peterson trough (Miralda-Escudé 1998). Unfortunately, the highly luminous quasars presently observed probably

⋆E-mail: peng@tapir.caltech.edu

ionize their surroundings on scales of several megaparsecs; the consequent reduction in optical depth precludes observation of the red damping wing (Cen & Haiman 2000; Madau & Rees 2000). The only hope of detecting a damping wing would be to discover objects that ionize only a small region of the surrounding IGM: either a high-redshift γ-ray burst (which has a very short duty cycle) or less luminous quasars or galaxies (which can be detected through gravitational lensing; Ellis et al. 2001). Alternatively, one might hope to detect the Lyα halo surrounding a high-redshift source as Lyα photons scatter and redshift in the surrounding neutral IGM (Loeb & Rybicki 1999). This also suffers from the difficulty that sources tend to ionize their surroundings; furthermore, the low surface brightness of the halo implies that detection is probably only possible with the *New Generation Space Telescope* (*NGST*).

What can be done with present-day technology? Clearly, we need absorption-line probes that are still unsaturated when the IGM is predominantly neutral. This is possible if the absorbers are much less abundant than hydrogen or have very small oscillator strengths. They should have ionization potentials similar to that of hydrogen in order to trace the H I fraction as faithfully as possible. In addition, their absorption lines must lie redward of the hydrogen Lyα wavelength $\lambda = 1216$ Å in order to avoid confusion with the lower-redshift Lyα forest. In this paper, I suggest metal absorption lines as a probe of the neutral IGM. Metals are a natural probe: for a fully neutral IGM, $\tau_{\mathrm{H\,Ly}\alpha} \sim 10^5$ at $z \sim 6$, and while the oscillator strengths of metal ultraviolet/optical transitions ($f \sim 10^{-2}$–1) are roughly comparable to that of hydrogen Lyα, the abundance by number of metals should be lower by $\sim 10^{-6}$–10^{-5}, implying $\tau_{\mathrm{metals}} \sim 10^{-2}$–1. The most uncertain aspect of this calculation is the degree to which an IGM polluted by metals can still remain neutral. I argue that, because overdense regions are the first to be polluted with metals but the last to be permanently ionized (owing to the short recombination time), a scenario of a neutral but metal-polluted IGM is plausible. None the less, because of this uncertainty, a null detection of absorption will only yield a constraint on the joint metallicity/ionization state of the IGM. A positive detection, however, may be our best hope of unveiling an almost fully neutral IGM with observations of high-redshift quasars in the near future. In all numerical estimates, I assume a ΛCDM cosmology with $(\Omega_{\mathrm{M}}, \Omega_\Lambda, \Omega_{\mathrm{b}}, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$.

2 CAN METALS BE SEEN AT HIGH REDSHIFT?

It is useful to begin by ruling out some promising possibilities. The best absorption-line probes would involve primordial elements, which are not afflicted with uncertainties associated with the (unknown) high-redshift metal abundance. The most obvious candidate, hydrogen 21-cm absorption, has too weak an oscillator strength, the optical depth across a Hubble volume is

$$\tau = 4.2 \times 10^{-3} \langle x_{\mathrm{H\,I}} \rangle \left(\frac{T_{\mathrm{CMB}}}{T_{\mathrm{S}}} \right) \left(\frac{1+z}{7} \right)^{1/2}$$

(where T_{S} is the spin temperature), and the observational difficulties in detecting a signal are formidable[1] (Shaver et al. 1999). Similarly, $\mathrm{H_2}$, which lacks a dipole moment, has too low an oscillator strength. HD does have a dipole moment and higher oscillator strength (by a factor of $\sim$1000) but insufficient to offset its low primordial abundance $x_{\mathrm{HD}} \sim 10^{-7}$. Likewise, the optical depth of lithium is appreciable only at high redshift $z \sim 500$ (Loeb 2001). Deuterium has roughly the right abundance ($\sim 10^{-5}$) and oscillator strength (same as H), but its Lyα wavelength lies too close to the H Lyα transition (offset by only $\sim$82 km s^{-1}) to be useful. He I has a metastable 2^3S state, which becomes populated during the recombination cascade. Resonance-line absorption from this state occurs at long wavelengths $\sim$4471, 5876 Å, which are redward of hydrogen Lyα as required. However, owing to the relatively short lifetime, $\sim 10^4$ s, of this state, it is appreciably populated only in highly dense and significantly ionized gas:

$$n(2^3\mathrm{S})/n(\mathrm{He}^+) = 5.8 \times 10^{-6} T_4^{-1.18} \Big/ \left(1 + 3110 T_4^{-0.5} n_{\mathrm{e}}^{-1}\right) \approx 1.9 \times 10^{-9} T_4^{-0.7} n_{\mathrm{e}}$$

(Clegg 1987), where n_{e} is the electron number density in cm^{-3}. The only possibility left is metal lines.

Table 1. Metal absorption lines that may potentially be observable in a nearly neutral IGM. I_i is the ionization potential of the ion, λ and f are the absorption wavelength and oscillator strength, and τ is the optical depth of the line across a uniform IGM at $z = 6.3$, assuming a metallicity of $Z = 10^{-2.5}\,\mathrm{Z}_\odot$. Only atomic species with $I_i > 13.6$ eV are likely to be abundant, since the Universe is optically thin to radiation below the Lyman limit.

Ion	I_i (eV)	λ (Å)	f	τ ($z = 6$)
O I	13.6	1302	0.05	0.14
Fe II	16.1	2383	0.3	0.05
Si II	16.34	1260	1.18	0.13
C II	24.4	1334	0.127	0.16

The optical depth of a line across a uniform IGM that has been homogeneously polluted by metals is

$$\tau = 0.16 x_i \left(\frac{X_a}{2.7 \times 10^{-6}} \right) \left(\frac{f}{0.05} \right) \left(\frac{\lambda}{1302\,\text{Å}} \right) \left(\frac{1+z}{7} \right)^{3/2}, \quad (1)$$

where x_i is the fraction of the metal atoms a in the appropriate ionization state i, $X_a = (Z/\mathrm{Z}_\odot) \times (n_a/n_{\mathrm{H}})_\odot$ is the abundance by number of metal a relative to hydrogen, f and λ are the oscillator strength and rest wavelength of the appropriate transition. I adopt $(n_{\mathrm{C},\odot}, n_{\mathrm{O},\odot}, n_{\mathrm{Si},\odot}, n_{\mathrm{Fe},\odot}) = (3.58, 8.49, 0.33, 0.295) \times 10^{-4} n_{\mathrm{H},\odot}$ for the solar abundance by number of carbon, oxygen, silicon and iron, respectively (Anders & Grevesse 1989). For some metals, particularly Si, this may be an underestimate: the supernovae of supermassive stars which are thought to form out of very low/zero-metallicity gas overproduce α elements such as Si, S and Ca by factors of a few compared to solar ratios (Heger & Woosley 2002; see fig. 1 of Oh et al. 2001). In Table 1, I list various lines that I have identified as promising tracers of the IGM ionization state:[2] those with ionization potentials close to that of hydrogen and strong resonance lines redward of hydrogen Lyα. If the IGM is polluted to a metallicity of $Z \sim 10^{-2.5}\,\mathrm{Z}_\odot$ at $z \sim 6$, the optical depths are fairly high: there would be a flux decrement of $\sim$5–20 per cent blueward of these lines, which is certainly detectable in high signal-to-noise ratio spectra. I exclude ions with ionization potential $I_i < 13.6$ eV: such ions should be rare, as the Universe is optically thin to radiation at these wavelengths and these atoms are very easily ionized to the next stage. Submillimetre

[1] However, 21-cm *emission* from the neutral IGM might be detectable with the Square Kilometer Array (Tozzi et al. 2001).

[2] Tables for the atomic constants are available at the website http://www.pa.uky.edu/~verner/lines.html

fine-structure lines of metals have oscillator strengths that are too low for absorption to be detectable. Although (as we shall see) metal-line absorption probably produces a fluctuating forest rather than a mean flux decrement, the relative values of τ provide a good estimate of the importance of various transitions.

O I is a particularly promising tracer. Its ionization potential $I_i = 13.618$ eV is only $\Delta E = 0.19$ eV higher than that of hydrogen: therefore a detection of O I almost certainly signals the presence of neutral hydrogen. In fact, oxygen should be locked in tight charge exchange equilibrium with hydrogen, through the processes (Osterbrock 1989)

$$\mathrm{O} + \mathrm{H}^+ \rightarrow \mathrm{O}^+ + \mathrm{H}^0$$
$$\mathrm{O}^+ + \mathrm{H}^0 \rightarrow \mathrm{O} + \mathrm{H}^+$$

The equilibration time-scale is

$$\sim \frac{1}{k_{\mathrm{ce}} n_{\mathrm{H\,I}}} \sim 1.7 \times 10^5 x_{\mathrm{H\,I}} \Delta \left(\frac{1+z}{7}\right)^3 \ \mathrm{yr}$$

(where Δ is the gas overdensity), much shorter than the Hubble time. Therefore the O I fraction should be very accurately given by

$$\frac{n_{\mathrm{O}}}{n_{\mathrm{O}^+}} = \frac{9}{8} \frac{n_{\mathrm{H}^0}}{n_{\mathrm{p}}} \exp\left(\frac{\Delta E}{k_{\mathrm{B}} T}\right),$$

where $\exp(\Delta E / k_{\mathrm{B}} T) \rightarrow 1$ for $k_{\mathrm{B}} T \gg \Delta E = 0.19$ eV.

The Si II 1260 Å line and C II 1334 Å lines are other promising absorption features, which are well known to be present in neutral gas. Note that Si II has two other transitions near these wavelengths, which are unlikely to be observable because of their weaker oscillator strengths: a 1304 Å ($f = 0.0871$, $\tau \approx 0.07\tau_{\mathrm{O\,I}}$) line and a $\lambda = 1526$ Å ($f = 0.132$, $\tau \approx 0.11\tau_{\mathrm{O\,I}}$) line. From Table 1, we see that O I (1302 Å), Si II (1260 Å) and C II (1334 Å) lines will be the most prominent absorption features.

There are two large uncertainties in the above estimates. The first is the mean metallicity of the IGM at high redshift: Will the IGM contain enough metals for this observational probe to work? The very short time-scale on which massive stars evolve, $\sim 10^6$–10^7 yr, implies that the IGM could have been polluted very early. There are a number of observational hints that this is the case. There is little or no evolution in the observed supersolar metallicities of SDSS quasars from $z \sim 6$ to $z \sim 2$, implying that the first stars around quasars must have formed at $z > 8$ (Pentericci et al. 2002). The mean metallicity of the IGM at $z \approx 3$ at the lowest observable column densities is $Z \sim 10^{-2.5}$ $\mathrm{Z}_{\odot}$ (Songaila 1997; Ellison et al. 2000). From the spectra of 32 quasars in the redshift range 2.31–5.86, Songaila (2001) finds no evolution in the mean universal metallicity of the IGM in the redshift range $z = 1.5$–5.5. The *minimum* value she finds at $z = 5$ is $Z > 10^{-3.5}$ $\mathrm{Z}_{\odot}$. Very plausible theoretical scenarios can be constructed in which an early generation of stars pollute the intergalactic medium to mean metallicities $Z \approx 10^{-2.5}$ $\mathrm{Z}_{\odot}$ with volume filling factors >20 per cent by $z \sim 9$, without significant hydrodynamic perturbation of the IGM (Madau, Ferrara & Rees 2001).

In fact, for reionization to take place, a significant amount of star formation and thus metal ejection must take place. The same massive stars which produce ionizing photons also produce metals; there is a direct relation between the two. Madau & Shull (1996) find, largely independent of initial mass function (IMF), that ∼1.8 MeV in the ionizing continuum is produced per metal baryon. A similar relation (∼3.3 MeV per metal baryon) holds for supermassive stars $M > 100$ $\mathrm{M}_{\odot}$ thought to form out of metal-free gas (Bromm, Kudritzki & Loeb 2001; Heger & Woosley 2002). We can therefore write:

$$n_\gamma = 0.7 \left(\frac{\bar{Z}}{10^{-2.5}\,\mathrm{Z}_{\odot}}\right) \left(\frac{f_{\mathrm{esc}}}{0.1}\right) + n_\gamma^{\mathrm{QSO}}, \tag{2}$$

where n_γ is the number of ionizing photons per baryon in the Universe, $\bar{Z}$ is the mean metallicity of the Universe, f_{esc} is the escape fraction of ionizing photons from their host haloes, and n_{QSO} is the contribution from quasars (which produce ionizing photons but no metals). The escape fraction f_{esc} is highly uncertain, with estimates ranging from ∼5 per cent in the local Universe (Leitherer et al. 1995; Dove, Shull & Ferrara 2000) to as high as ∼50 per cent in highly luminous Lyman break galaxies (Steidel, Pettini & Adelberger 2001). However, even for $f_{\mathrm{esc}} \sim 100$ per cent, the mean metallicity should be reasonably high towards the tail end of the reionization process, $\bar{Z} \sim 10^{-3.5}$ $\mathrm{Z}_{\odot}$. Another uncertainty is the filling factor of metal-polluted regions f_Z. We show in Section 3 that most reasonable values of f_Z should give rise to an absorption signal. Significant retention of metals by their host haloes is unlikely because of the shallow potential wells predominant at these early epochs; in addition, metal-enriched material is much more easily ejected from haloes than the ambient gas (MacLow & Ferrara 1999). The only case where the Universe can be reionized without significant co-production of metals is if quasars are the dominant ionizing source. Again, this is highly uncertain, but note that the comoving emissivity of quasars at $z = 5$, as inferred from the quasar luminosity function, is insufficient to keep the Universe reionized at $z = 5$ by an order of magnitude (Madau, Haardt & Rees 1999; Fan et al. 2001a); the density of quasars at high redshift is also constrained by the lack of faint red unresolved objects in the *Hubble Deep Field* (Haiman, Madau & Loeb 1999). Except for the very early stages of reionization (which are unlikely to be accessible with present-day instruments, in any case), the IGM is likely to be polluted to sufficiently high metallicity to make metal-line absorption studies feasible.

The second, much larger uncertainty is whether regions which are pre-enriched with metals can still remain neutral. As previously noted, the filling factor of ionized regions should be considerable once the IGM is polluted up to metallicities $Z \sim 10^{-3.5}$–$10^{-2.5}$ $\mathrm{Z}_{\odot}$, unless the escape fraction is very small, $f_{\mathrm{esc}} < 1$ per cent, and it is possible that all metal-polluted regions will also be ionized. Indeed, for f_{esc} greater than a few per cent, the typical size of H II regions at $z \sim 9$ will be greater than that of the metal-laden supernovae-driven superbubble (Madau et al. 2001); an ionization front precedes the metal-pollution front. Even if the ionizing-photon escape fraction is extremely small, the metal-pollution front is likely to collisionally ionize the IGM by shock heating it to $T > 10^{4.5}$ K, owing to the high speed of the expanding superbubble.

However, it is important to realize that hydrogen recombination times at high redshift,

$$t_{\mathrm{rec}} \approx 3 \times 10^8\, x_{\mathrm{e}}^{-1} \Delta^{-1} \left(\frac{1+z}{10}\right)^{-3} \left(\frac{T}{10^4\,\mathrm{K}}\right)^{0.7} \ \mathrm{yr},$$

are short compared to the Hubble time,

$$t_{\mathrm{H}} = 9 \times 10^8 \left(\frac{1+z}{10}\right)^{-1.5} \ \mathrm{yr},$$

so the ionization fraction,

$$x_{\mathrm{e}} = \frac{1}{1 + (t/t_{\mathrm{rec}})} \approx \frac{t_{\mathrm{rec}}}{t_{\mathrm{H}}} = 0.3\Delta^{-1} \left(\frac{1+z}{10}\right)^{-1.5} \left(\frac{T}{10^4\,\mathrm{K}}\right)^{0.7},$$

and the gas could become ∼70 per cent neutral. The lifetime of sources is likely to be short: the lifetime of massive stars is

$t_{\rm MS} \sim 10^6$–10^7 yr, and the duty cycle of quasars is probably of the order of the Eddington time-scale $\sim 10^7$ yr [such a lifetime is consistent with current observations of quasars (see Blandford 1999, and references therein)]. Early reionization in the pre-overlap era is probably a highly stochastic process in which regions of the IGM are ionized, polluted with metals, and then recombine and become largely neutral until another source lights up. While early reionization is temporary and the ionization state of any given region of the IGM fluctuates, metal pollution is a permanent process and the metallicity of the IGM rises monotonically. Note also that, although high-density filaments may initially be collisionally ionized by the accretion shock during gravitational collapse, the gas will eventually cool and recombine.

In particular, overdense regions are the first to be polluted up to high metallicities (owing to their proximity to sites of star formation) but they are the last to remain permanently ionized (owing to the short recombination times). From numerical simulations, Cen & Ostriker (1999) find that metallicity depends very strongly on local density: at every epoch, higher-density regions have much higher metallicities than lower-density regions. In fact, the highest-density regions quickly saturate at near-solar metallicities early on. These results are in much better agreement with observations than scenarios in which metal pollution is uniform. Miralda-Escudé, Haehnelt & Rees (2000) point out that in an inhomogeneous Universe reionization should begin in voids and gradually penetrate into overdense regions; the regions of highest density are the last to be reionized. This picture is strongly substantiated in numerical simulations of reionization (Gnedin 2000; though also see Razoumov et al. 2001). Although the ionizing sources themselves tend to be embedded in the overdense regions, most of the gas in the filaments tends to remain neutral: ionizing photons quickly escape along underdense directions into the voids. These arguments suggest that a line of sight to a high-redshift quasar will intersect regions at or above the mean density which are largely neutral but none the less polluted with metals. Such overdense regions are the most likely sites to produce the metal absorption lines we seek.

The temperature of metal-polluted gas is likely to be $\sim 10^4$–10^5 K (Madau et al. 2001). It can be shock heated up to $\sim 10^7$ K by the expanding superbubble, but cools rapidly by Compton cooling off the cosmic microwave background (CMB) on a time-scale

$$t_{\rm comp} = 2.3 \times 10^8 \left(\frac{1+z}{10}\right)^{-4} \ {\rm yr}.$$

Below $T \sim 10^4$ K the gas recombines and Compton cooling (as well as hydrogen line cooling) is no longer effective; the gas then cools only by adiabatic expansion on the Hubble expansion time-scale. In highly overdense and metal-polluted regions, metal-line cooling will become important, but these correspond to collapsed haloes which are in any case unstable to star formation. $T \sim 10^4$ K is also the equilibrium temperature if a photoionizing background is present.

A final concern might be that the outflows that deposit metals in the IGM produce peculiar motions which broaden the metal absorption lines unacceptably. However, note that expanding metal pollution bubbles stall in pressure balance with a pre-heated IGM (Madau et al. 2001). This gas is eventually re-accreted on to collapsing large-scale structure. Strong residual turbulent motions are unlikely since the Lyα forest (even C IV absorbers) at $z \sim 3$ is observed to be remarkably quiescent, with linewidths consistent with thermal broadening alone.

3 THE O I FOREST

3.1 A simple model for gas clumping and metal pollution

Let us now quantify the effects of gas clumping in the IGM. Miralda-Escudé et al. (2000) find the following to be a good fit to the probability distribution by volume of gas overdensities Δ seen in the LCDM numerical simulations of Miralda-Escudé et al. (1996):

$$P_{\rm V}(\Delta)\,{\rm d}\Delta = A \exp\left[-\frac{(\Delta^{-2/3} - C_0)^2}{2(2\delta_0/3)^2}\right] \Delta^{-\beta}\,{\rm d}\Delta, \tag{3}$$

where they tabulate values for A, β, C_0 and δ_0 at different redshifts $z = 2, 3, 4$ and 6. One can extrapolate their results to higher redshifts by using $\delta_0 = 7.61/(1+z)$ (which fits their results to better than 1 per cent), assuming $\beta = 2.5$ (corresponding to an isothermal slope for high-density haloes), and fixing A and C_0 by requiring the total mass and volume to be normalized to unity. Their fit is valid if the gas is smoothed on the Jeans scale for a gas temperature $T \sim 10^4$ K; we have argued that high-redshift metal-polluted gas should indeed be at approximately this temperature. The fraction of baryons above a given overdensity Δ_i by volume and by mass is then given by

$$f_{\rm V}(\Delta_i) = \int_{\Delta_i}^{\infty} P_{\rm V}(\Delta)\,{\rm d}\Delta$$

and

$$f_{\rm M}(\Delta_i) = \int_{\Delta_i}^{\infty} \Delta P_{\rm V}(\Delta)\,{\rm d}\Delta$$

respectively.

In order to compute the optical depth of the IGM to metal-line absorption, we need to specify two unknown functions, the metallicity $Z(\Delta, z)$ and ionization fraction $x_i(\Delta, z)$ of the IGM as a function of overdensity and redshift, but only in the combination $Y(\Delta, z) \equiv x_i(\Delta, z) Z(\Delta, z)$. We can make progress by making some simplifying assumptions. The growth of metallicity has two free parameters: the mean metallicity of the universe $\bar{Z}$ (a proxy for the total amount of star formation), and the volume filling factor of metal-polluted regions f_Z. These two parameters are obviously interrelated, but because of the large uncertainties we treat them as independent free parameters, with an upper bound on the filling fraction

$$f_Z < 0.2 \max\left[(\bar{Z}/10^{-2.5}\,{\rm Z}_\odot)^{3/5}, (\bar{Z}/10^{-2.5}\,{\rm Z}_\odot)\right],$$

where the normalization is based on the model of Madau et al. (2001). $f_Z \propto Z^{3/5}$ mimics the energy dependence of the adiabatic Taylor–Sedov solution (putting all the stars together), while $f_Z \propto Z$ is correct in the limiting case where metal pollution occurs uniformly throughout space. Filling factors as low as ~ 1 per cent are possible if the metal-enriched ejecta have magnetic fields that resist mixing with the IGM; metal-polluted regions could be restricted to magnetized 'streaks' which are then sheared and distorted by subsequent gravitational clustering (Madau et al. 2001). The growth of reionization has two free parameters, the filling factor Q of ionized regions, and the overdensity Δ_i up to which gas is ionized. Again, these parameters are obviously related, but we can make the approximation that they are decoupled, with the following argument. The early stages of reionization are characterized by reionization of the voids ($\Delta_i < 1$) and growth of the filling factor of ionized regions Q. However, at some point overlap occurs ($Q \approx 1$), and overdense regions start to be reionized, and Δ_i grows (this hinges on the fact that high-density regions only occupy a small fraction of the volume). As noted by Miralda-Escudé et al. (2000), the value of $\Delta_i^{\rm overlap}$

at which $Q \approx 1$ depends on the nature of the ionizing sources: for dim but numerous sources $\Delta_i^{\rm overlap} \sim 1$, whereas for bright but rare sources $\Delta_i^{\rm overlap}$ is larger, since higher-density regions have to be ionized before percolation can occur. We therefore treat it as a free parameter.

The progress of reionization and the growth in metallicity $\bar{Z}$ are coupled via equation (2). In particular, the relation between (Q, Δ_i) and $\bar{Z}$ depends on the escape fraction of ionizing photons $f_{\rm esc}$ and the relative contribution of QSOs to reionization, $f_{\rm QSO} \equiv n_\gamma^{\rm QSO}/n_\gamma$. In the early stages of reionization, recombinations are unimportant and $Q \propto n_\gamma \propto \bar{Z}$. In the late stages when recombinations dominate the consumption of ionizing photons, we can relate $\bar{Z}$ and the overdensity Δ_i up to which gas is ionized by equating the number of ionizing photons per baryon with the mean number of recombinations per baryon in a Hubble time of the ionized gas:

$$n_\gamma(\bar{Z}) = t_{\rm H}\alpha\bar{n}C_{\rm H\,II}(\Delta_i), \tag{4}$$

where

$$C_{\rm H\,II}(\Delta_i) = \int_0^{\Delta_i} \Delta^2 P_V(\Delta)\,{\rm d}\Delta$$

is the clumping factor of ionized gas. This assumes that most star formation and hence metal pollution occurred during the last Hubble time. The relationship between Δ_i and $\bar{Z}$ is shown in Fig. 1, for different values of $f_{\rm esc}/(1 - f_{\rm QSO})$: the smaller the value of this parameter, the larger the amount of star formation and thus metal pollution $\bar{Z}$ needed to keep the Universe ionized.

With this simple picture we can make an Ansatz for the evolution of $Y(\Delta, z)$. I assume that metal pollution begins in the most overdense regions, while reionization begins in the most underdense regions. At any given epoch, I assume $Z \approx Z_{\rm crit}$ for $\Delta > \Delta_i^{fz}$ and

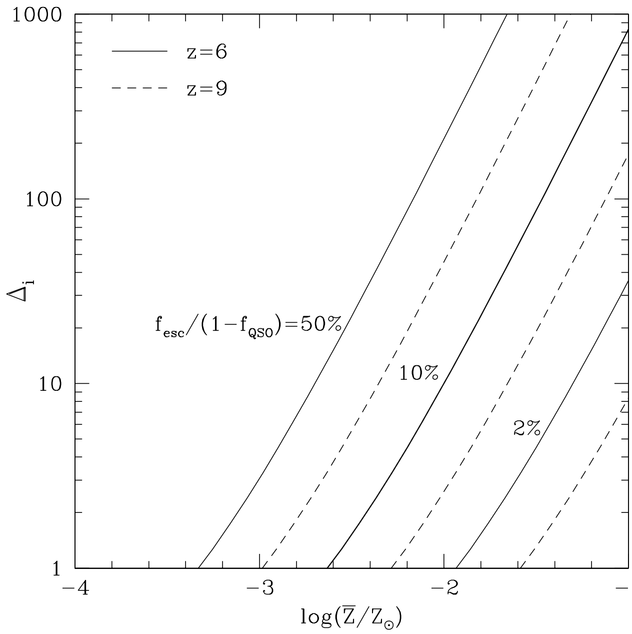

Figure 1. Overdensity Δ_i up to which the Universe is ionized in the post-overlap era, as a function of the mean metallicity of the Universe $\bar{Z}$, assuming a (fairly robust) relation between the metals and ionizing photons produced by massive stars. Solid lines are for $z = 6$, and dashed lines for $z = 9$. The curves are plotted for different values of $f_{\rm esc}/(1 - f_{\rm QSO})$ where $f_{\rm esc}$ is the escape fraction of ionizing photons from star-forming haloes, and $f_{\rm QSO}$ is the fractional contribution of quasars to the ionizing background. The relation between Δ_i and $\bar{Z}$ shown here is used in Fig. 3.

$Z \approx 0$ otherwise. Similarly, I assume the neutral fraction $x_{\rm H\,I} \approx 1$ for $\Delta > \Delta_i^{\rm H\,I}$ and $x_{\rm H\,I} \approx 0$ otherwise. The value of Δ_i^{fz} is given by the implicit equation $f_{\rm V}(\Delta_i) = f_Z$, while $Z_{\rm crit} = \bar{Z}/f_{\rm M}(\Delta_i^{fz})$. The value of $\Delta_i^{\rm H\,I}$ is $\Delta_i^{\rm H\,I} < 1$ during the pre-overlap phase and is given by equation (4) in terms of $\bar{Z}$, $f_{\rm esc}$ and $f_{\rm QSO}$ in the post-overlap phase, when recombinations are important. There are two limits to consider. In the early stages of reionization, when $\Delta_i^{\rm H\,I} < \Delta_i^{fz}$, the high-density regions where metals reside are largely neutral, $x_i \sim 1$. The growth in Y with time is dominated by the increase in metallicity. This epoch can therefore be characterized by the two parameters $(\bar{Z}, f_Z)$. In the late (post-overlap) stages of reionization, when $\Delta_i^{\rm H\,I} > \Delta_i^{fz}$, the evolution in Y is dominated by the evolution of x_i, when increasingly dense (and metal-polluted) regions become ionized. In this regime the model can be specified in terms of the parameters $(\bar{Z}, f_Z, f_{\rm esc}/(1 - f_{\rm QSO}))$, and $\Delta_i^{\rm H\,I}$ can be computed from equation (4). The transition between these two regimes occurs when the volume filling fraction of metal-polluted regions and neutral regions are comparable, $f_Z \sim 1 - Q$. Since we expect $f_Z < 0.2$ (metal pollution should not be effective in voids, which occupy most of the volume), the transition regime occurs roughly at the point of overlap, when $Q \rightarrow 1$. The transition occurs very quickly: $1 - Q$ evolves extremely rapidly at the point of overlap, when the mean free path (mfp) of ionizing photons rises on a very short time-scale (of the order of the light traveltime across an H II region) and the ionizing background increases dramatically. By contrast, Z evolves on the time-scale for structure formation or $t_{\rm H}$. In fact, $\dot{Z}$ may drop at the point of overlap since the sudden rise in the IGM temperature and Jeans mass could cause a drop in the comoving star formation rate (Barkana & Loeb 2000).

In summary, for most of the gas, the parameter $Y \equiv x_i Z$ rises in the early stages of reionization as the metallicity grows, peaks at an epoch roughly corresponding to the overlap epoch, and then falls as the gas is reionized. Note that, for higher Δ, the peak value of Y is higher and occurs at progressively later epochs, since gas at higher overdensities is only reionized at later times, and so there is a longer time interval for metal pollution to take place. We now examine the observational predictions of this simple model.

3.2 Observational predictions

We begin by computing the mean Gunn–Peterson absorption in a clumpy and inhomogeneously polluted Universe. The optical depth due to regions of overdensity Δ is given by

$$\tau(\Delta, z) = \Delta \frac{Z(\Delta, z)}{\bar{Z}} \frac{x_i(\Delta, z)}{\bar{x}_i} \tau_0(\bar{Z}, \bar{x}_i, z),$$

where τ_0 is the optical depth of the line in a uniform IGM that is uniformly polluted to a metallicity $\bar{Z}$ and has a mean ionization fraction $\bar{x}_i$. The mean metal-line Gunn–Peterson absorption $\mathcal{A}$ due to gas with $\Delta > \Delta_{\rm crit}$ is then given by

$$\mathcal{A}(\Delta_{\rm crit}) = \langle 1 - {\rm e}^{-\tau} \rangle = \int_{\Delta_{\rm crit}}^{\infty} (1 - {\rm e}^{\tau(\Delta)}) P(\Delta)\,{\rm d}\Delta. \tag{5}$$

Note that in general $\mathcal{A}(\Delta_{\rm crit})$ is smaller than $\mathcal{A}$ for a uniform IGM. For instance, for $\Delta_{\rm crit} \sim 3$ at $z = 6$ and $\bar{Z} = 10^{-2.5}$ Z$_\odot$, we have $\tau_{\rm eff} \approx 0.02 x_i$, rather than $\tau \approx 0.14 x_i$ for a uniform IGM. $\tau_{\rm eff}$ falls exponentially with increasing Δ_i, because of the exponentially small fraction of baryons at high overdensities.

The tight charge exchange equilibrium between O I and H I implies that there is a direct relation between their effective optical depths, *independent* of gas clumping or the nature of the ionizing radiation field:

$$\tau_{\rm OI}^{\rm eff} = 1.1 \times 10^{-6} \left(\frac{\langle Z \rangle}{10^{-2}\,{\rm Z}_{\odot}} \right) \tau_{\rm HI}^{\rm eff}, \tag{6}$$

where $\langle Z \rangle$ is the H I column-density-weighted metallicity of the Universe (as opposed to the mean metallicity $\bar{Z}$; in general $\langle Z \rangle > \bar{Z}$). Therefore, if we could measure both $\tau_{\rm OI}^{\rm eff}$ and $\tau_{\rm HI}^{\rm eff}$, we can obtain a robust and relatively model-independent measure of the metallicity of the high-redshift Universe. Such a fortuitous occasion might arise if we could observe a high-redshift γ-ray burst, which does not exhibit a strong proximity effect, and therefore allows measurement of $\tau_{\rm HI}^{\rm eff}$ by measuring the shape of the damping wing. The transmitted flux recovers its full value at $\Delta\lambda/\lambda \sim 0.1$ redward of the damping wing (Miralda-Escudé 1998), so a clean separation of the contribution of O I absorption at $1302(1+z_{\rm s})$ Å ($\Delta\lambda/\lambda \sim 0.07$) might be possible, particularly if the shape of the damping wing is well constrained. Although O I absorption will probably produce a fluctuating forest, $\tau_{\rm OI}^{\rm eff}$ can be obtained by smoothing the spectrum. The ability to measure a mean O I decrement of a few per cent depends on the accuracy to which sky lines and absorption from other sources can be ruled out (see discussion at end of section). In the absence of a measurement of $\tau_{\rm HI}^{\rm eff}$, a conservative lower bound on the metallicity of the high-redshift Universe can still be placed from equation (1) by assuming the IGM to be fully neutral, $x_i \sim 1$, and uniform (since $\langle \tau_{\rm OI} \rangle > \tau_{\rm OI}^{\rm eff}$).

Metals in the high-redshift IGM will probably not produce a Gunn–Peterson-like absorption trough but rather a forest of metal lines which – particularly in the case of O I – will provide a snapshot of neutral regions along the line of sight. Schaye (2001) shows that many properties of the Lyα forest can be understood by associating the characteristic length-scale of absorbers with the local Jeans length. This allows us to associate a column density for an ion i with a given overdensity Δ:

$$N_i = 6.2 \times 10^{13}\,{\rm cm}^{-2}\, x_i \times \left(\frac{X_a}{2.7 \times 10^{-6}} \right) \left(\frac{1+z}{7} \right)^{1/2} \left(\frac{T}{10^4\,{\rm K}} \right)^{1/2} \left(\frac{\Delta}{3} \right)^{1/2}, \tag{7}$$

where x_i and X_a are the ionization fraction and metal number abundance. This corresponds to an equivalent width

$$\frac{W_\lambda}{\lambda} = 5.8 \times 10^{-5} \left(\frac{N_i}{10^{14}\,{\rm cm}^{-2}} \right) \left(\frac{f}{0.05} \right) \left(\frac{\lambda}{1302\,{\rm Å}} \right),$$

where I have used the fact that lines will always be on the linear portion of the curve of growth. This gives an observed equivalent width

$$W_\lambda \approx 0.53\,{\rm Å} \left(\frac{N_{\rm OI}}{10^{14}\,{\rm cm}^{-2}} \right) \left(\frac{\Delta}{3} \right), \tag{8}$$

which is certainly detectable with extended integration on Keck. At a given overdensity Δ, the O I 1302 Å and Si II 1260 Å equivalent widths are roughly equal; the increased oscillator strength of the Si II line compensates for its reduced abundance. Since on average W_i increases monotonically with Δ, for any given W_i, there exists some Δ_i such that $\Delta > \Delta_i \Rightarrow W > W_i$. The mean spacing between lines with $W > W_i$ can be estimated by the mean separation between contours of overdensity Δ_i in the Universe. This can be estimated as (Miralda-Escudé et al. 2000)

$$l_{\rm mfp} = l_0 [1 - F_V(\Delta_i)]^{-2/3}, \tag{9}$$

where $F_V(\Delta_i)$ is the fraction of the volume with $\Delta < \Delta_i$, and $l_0 H = 60\,{\rm km\,s^{-1}}$ (basically determined by the Jeans length) is a good fit to numerical simulations.

There is only a finite stretch of the spectrum over which O I and Si II absorption can be seen before it becomes confused with the hydrogen Lyα forest. Suppose we observe a bright quasar which ionizes its surroundings so that the damping wing of the Gunn–Peterson trough does not extend redward of the Lyα line. A photon can redshift for $d = \delta\lambda/\lambda \approx 20\,000$ km s^{-1} from the O I absorption edge at $\lambda_i = 1302(1+z_{\rm s})$ Å and $d \approx 10\,000$ km s^{-1} from the Si II absorption edge at $\lambda_i = 1260(1+z_{\rm s})$ Å, before it encounters the H I Gunn–Peterson trough at $\lambda_{\rm GP} \sim 1216(1+z_{\rm s})$ Å (this interval is actually somewhat smaller, as a result of the finite width of Lyα and N V emission lines). The mean number of observable lines with $N > N_i$ is

$$N_{\rm lines}(\lambda_{\rm GP} < \lambda < \lambda_i) \sim l_{\rm mfp}/d. \tag{10}$$

Below we shall compute this quantity for several different models of metal pollution and reionization. Note that the probability that no lines with $N > N_i$ are seen is $\exp(-\lambda_i/l)$.

In Fig. 2, we show the mean observable number of O I lines above a given column density $\tilde{N}_{\rm OI}$ detectable in the pre-overlap phase. In this phase, $(\bar{Z}, f_Z)$ are free parameters. For a given f_Z, the column densities can be rescaled to the assumed mean metallicity via

$$N_{\rm OI} = \tilde{N}_{\rm OI} \left(\frac{Z}{10^{-2.5}\,{\rm Z}_{\odot}} \right).$$

We see that a few lines can be seen in the 10^{14}–10^{15} cm^{-2} range in the pre-overlap era for filling factors $f_Z \sim 10$ per cent. Somewhat more lines can be seen at higher redshift since $N_i \propto (1+z)^{1/2}$. The two distinct slopes in the relation can be easily understood. For a given $\bar{Z}$, increasing the metal filling factor f_Z increases the number

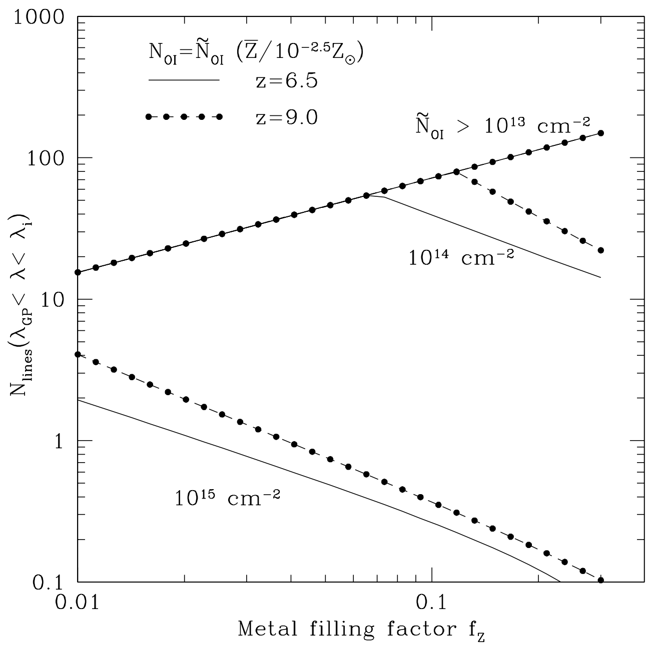

Figure 2. Number of O I lines above a given column density $N_{\rm OI}$ observable in the pre-overlap phase, when metal-polluted high-density regions are still largely neutral, as a function of the volume filling factor of metals f_Z. Solid lines are for $z = 6.5$, and dashed lines for $z = 9$. The column density scales directly with the assumed mean metallicity $\bar{Z}$. The slope of the relation depends on whether $\Delta_i^{N_{\rm OI}} < \Delta_i^{f_Z}$ (in which case $N_{\rm lines}$ increases with f_Z) or $\Delta_i^{N_{\rm OI}} > \Delta_i^{f_Z}$ ($N_{\rm lines}$ decreases with f_Z). See text for details. The number of lines with similar equivalent widths is comparable for C II, and roughly half for Si II.

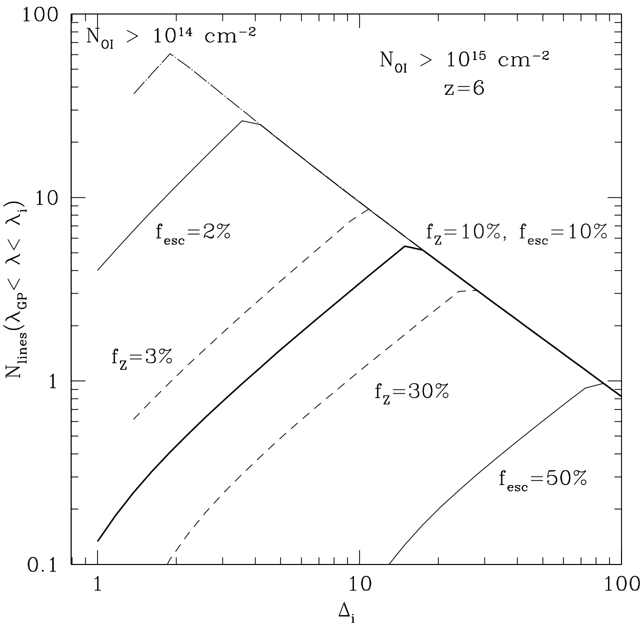

Figure 3. Number of O I lines with $N_{\rm O\,I} > 10^{15}$ cm^{-2} observable in the post-overlap era at $z = 6$ as a function of Δ_i, the overdensity to which the IGM is assumed to be ionized. The fiducial model (shown in bold) is for $f_Z = 10$ per cent, $f_{\rm esc} = 10$ per cent (for a substantial QSO contribution, $f_{\rm esc}$ should be replaced with $f_{\rm esc}/(1 - f_{\rm QSO})$). Other lines show the effect of varying f_Z, $f_{\rm esc}$ and $N_{\rm O\,I}$. The break in the slope of the relation can be easily understood; see text for details. The number of lines with similar equivalent widths is comparable for C II, and roughly half for Si II.

of patches along a line of sight to a quasar that are metal-polluted, but decreases their mean metallicity $Z_{\rm crit}$. For a low column density threshold, the former effect dominates and $N_{\rm lines}$ increases with f_Z; for a high column density threshold, increasing f_Z increases the number of lines that fall below threshold, and $N_{\rm lines}$ decreases with f_Z.

Similarly, in Fig. 3 we plot the mean number of observable lines that can be seen in the post-overlap era at redshift $z = 6$. The relation between $\bar{Z}$ and Δ_i shown in Fig. 1 has been assumed. The different lines illustrate the effect of varying the model parameters around the fiducial model ($f_{\rm esc}$, f_Z, $N_{\rm O\,I}^{\rm crit}$) = (0.1, 0.1, 10^{15} cm^{-2}). Again, the change in slope can be easily understood: As the ionized overdensity Δ_i increases, the number of lines seen initially increases, because of the larger implied star formation rate and thus higher $\bar{Z}$. At some point the decrease in filling factor of neutral regions overwhelms the increase in metallicity, and the number of lines decreases. The overdensity Δ_i at which this break occurs depends on $f_{\rm esc}/(1 - f_{\rm QSO})$ and f_Z, since these parameters control the relationship between Δ_i and $Z_{\rm crit} = \bar{Z}/f_Z$. For instance, the Universe is ionized up to a much higher Δ_i for a given $\bar{Z}$ if $f_{\rm esc}/(1 - f_{\rm QSO})$ is large. We see that it is quite plausible for us to see O I absorption lines with observed equivalent widths

$$W_\lambda \approx 5.3\,\text{Å} \left(\frac{N_i}{10^{15}\,\text{cm}^{-2}}\right)\left(\frac{1+z}{7}\right)$$

in the SDSS $z = 6.28$ quasar, which lies just at the tail end of reionization $\Delta_i \sim$ few.

Interesting (though model-dependent) constraints on $\bar{Z}$, $f_{\rm esc}$, $f_{\rm QSO}$ and f_Z might be possible from measurements of the O I forest. For instance, the length of the dark region and upper limit on the transmitted flux in the Lyα,β troughs give constraints on Δ_i for a given model of structure formation; Fan et al. (2001b) find for their $z = 6.28$ quasar that $\Delta_i \sim 3$. From Fig. 1 we see that this implies

$$\bar{Z} \approx 10^{-2.4} Z_\odot \left(\frac{f_{\rm esc}}{0.1}\right)\left(\frac{1 - f_{\rm QSO}}{1}\right)^{-1},$$

fairly high metallicities. From Fig. 3 the number of O I lines above a given column density in the post-overlap phase depends on f_Z and $f_{\rm esc}$; the observed number might constrain their value. The Universe is likely to be in the pre-overlap era if a very long Gunn–Peterson trough with no detectable flux is seen. From Fig. 3, the number of detectable lines above a given column density might constrain $\bar{Z}$ and f_Z. The numerical value of the constraints are of course very model-dependent and should not be overinterpreted. Still, some interesting statements might still be made with reasonable confidence. For instance, if no O I lines can be seen in the post-overlap era despite a deep Gunn–Peterson damping trough, then $\bar{Z}$ is low: this implies that the escape fraction of ionizing photons is close to unity and/or that quasars are the dominant ionizing source. Alternatively, the majority of the metals are highly ionized, either because most metals reside in voids (although this is unlikely given the finite speed at which metal pollution fronts can propagate), or because the high-density regions in which they reside are constantly illuminated by an ionizing source.

The main observational obstacle to detecting the O I forest is confusion with other sources of line absorption. Intrinsic absorption within the quasar host can be constrained by the relative absence of absorption features in the rest-frame 1216–1302 Å range of the large sample of lower-redshift quasars. Indeed, because of the reasonably wide wavelength interval in which O I and Si II absorption can be seen ($\sim$20 000 and $\sim$10 000 km s^{-1} respectively), at the shorter wavelengths within this range intrinsic absorption can be ruled out. Broad absorption-line (BAL) quasars could have winds that show such features, though usually the outflows are highly ionized. Confusion with long-wavelength metal lines such as C IV or Mg II from lower-redshift systems is another problem. Such an origin can be constrained by the absence of a damped Lyα system at the corresponding redshift in the low-redshift Lyα forest. The third and potentially most serious problem is the fact that the night sky becomes increasingly noisy at these near-IR wavelengths, and the atmospheric OH forest becomes important. The accuracy with which the O I forest can be detected therefore depends on the accuracy with which telluric features can be divided out via a standard star calibration. Also, there are stretches between the night-sky OH forest lines in which no absorption should be seen, so O I absorption can be identified if it falls within these regions. Ultimately, the presence of neutral gas can be corroborated with simultaneous detections of O I, Si II and possibly Fe II absorption features. A larger quasar sample that shows long stretches of complete H I Gunn–Peterson absorption and in which the density of O I and Si II absorption features is higher in higher-redshift quasars should be an unambiguous signature of almost fully neutral patches of gas at high redshift.

4 DISCUSSION

Could the O I, Si II and C II forest already be present in existing data? Published spectra of the four highest-redshift SDSS quasars show absorption features in the wavelength interval under consideration. However, for three of them [SDSS 1044−0125 ($z = 5.80$), 0836+0054 ($z = 5.82$) and 1306+0356 ($z = 5.99$)], these are unlikely to correspond to O I, Si II or C II absorption lines: unless they correspond to regions of anomalously high metallicity, the associated hydrogen column densities would be $N_{\rm H\,I} > 10^{20}$ cm^{-2}, and all flux at the hydrogen Lyα wavelength should be obliterated, while some flux is still seen there. These lines are probably associated with metal lines (e.g. Mg II, C IV) from lower-redshift absorbers, and illustrate a generic difficulty in observing the features proposed in this paper. On the other hand, O I lines are not ruled out in the $z = 6.28$ quasar because of the complete damping of flux at Lyα,β wavelengths. Indeed, we have seen that up to a few absorption lines with observed equivalent widths

$$W_\lambda \sim 5\,\text{Å}\left(\frac{1+z}{7}\right)\left(\frac{N_i}{10^{15}\,\text{cm}^{-2}}\right)$$

might be seen in the post-overlap era. However, because the spectra of Becker et al. (2001) have been smoothed to 4 Å pixel^{-1}, such lines are difficult to detect. Several candidates can probably be ruled out: two of them lie at the same wavelengths as bright sky emission lines and are probably due to imperfect sky subtraction, while a third line with $W_\lambda \sim 25$ Å lies very close to the rest-frame O I wavelength and could be due to intrinsic absorption. More cannot be said without careful study of the spectrum. A definitive detection of the O I, Si II and C II forest can probably only be done with much higher signal-to-noise ratio spectra of the same quasar.

The estimates in this paper can be addressed in much greater detail with numerical simulations. In particular, I used very simple Ansätze for the dependences of metallicity and ionization fraction with overdensity, $Z(\Delta)$ and $x_i(\Delta)$, which in fact should be highly stochastic and spatially varying. They can be much better modelled in a self-consistent fashion in simulations that attempt to model the metal pollution (Cen & Ostriker 1999; Aguirre et al. 2001) and radiative transfer (Gnedin 2000; Razoumov et al. 2002), particularly since the rise in metallicity and ionization fraction are interrelated. The spatial structure of the O I forest can be computed by shooting lines of sight through a simulation box. If the O I forest is indeed seen, such studies will be urgently needed to provide a more realistic interpretation of the observations.

The scenario in this paper is not significantly altered if a substantial X-ray background due to high-redshift supernovae (Oh 2001) or quasars (Venkatesan, Giroux & Shull 2001) is present. The large mean free path of hard photons means that they can ionize the IGM fairly uniformly, but beyond $x_{\rm e} \sim 0.1$ most of the energy of an energetic electron created goes into Coulomb heating the gas rather than collisional ionization (Shull & van Steenberg 1985); predominantly neutral regions should therefore still exist.

We will gain a wealth of information about early metal pollution and the reionization process if the O I and Si II forests are seen. They will be direct probes of the topology and history of gas clumping, metal pollution and reionization in the early Universe. As we have seen, if we assume a relation between the metals and ionizing photons produced by massive stars, they could potentially also provide indirect constraints on the escape fraction of ionizing photons from star-forming haloes and the quasar contribution to the ionizing background, and the filling factor of metal pollution. They may also give clues as to the nature of the ionizing sources: the structure of forest lines should look different if the Universe were reionized by rare but luminous sources as opposed to abundant but faint sources, since in the former case higher overdensity regions have to be ionized before overlap can be achieved. O I and H I will be locked in very tight charge exchange equilibrium at high redshift. If we are lucky enough to observe the rest-frame optical afterglow of a high-redshift γ-ray burst and measure both $\tau^{\rm eff}_{\rm H\,I}$ (from the damping wind) and $\tau^{\rm eff}_{\rm O\,I}$, we will have a direct measure of the mean metallicity of the Universe at high redshift, independent of gas clumping or the form of the ionizing radiation field. Otherwise, a lower limit on the metallicity from measurement of $\tau^{\rm eff}_{\rm O\,I}$ alone is possible. A null detection of the O I and Si II forests will yield constraints on the parameter $Y_i(\Delta) = x_i(\Delta)Z(\Delta)$, but a positive detection will be tremendously exciting and almost certainly signal the presence of almost fully neutral hydrogen at high redshift. To date, the O I and Si II forests may be our only probes of nearly neutral gas in the pre-reionization epoch observable with current technology.

ACKNOWLEDGMENTS

I am grateful to Michael Strauss for detailed comments, and Charles Steidel for an informative conversation on some of the observational issues. I also thank Xiaohui Fan, Avi Loeb, Evan Scannapieco and David Spergel for stimulating conversations, and Marc Kamionkowski for encouragement and advice. I acknowledge NSF grant AST-0096023 for support.

REFERENCES

Aguirre A., Hernquist L., Schaye J., Katz N., Weinberg D. H., Gardner J., 2001, ApJ, 561, 521
Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197
Barkana R., 2001, New Astron., 7, 85
Barkana R., Loeb A., 2000, ApJ, 539, 20
Becker R. H. et al., 2001, AJ, 122, 2850
Blandford R. D., 1999, in Merritt D., Sellwood J. A., Valluri M., eds, ASP Conf. Ser. Vol. 182, Galaxy Dynamics. Astron. Soc. Pac., San Francisco, p. 87
Bromm V., Kudritzki R. P., Loeb A., 2001, ApJ, 552, 464
Cen R., Haiman Z., 2000, ApJ, 542, L75
Cen R., Ostriker J. P., 1999, ApJ, 519, L109
Clegg R. E. S., 1987, MNRAS, 229, 31P
Dove J. B., Shull J. M., Ferrara A., 2000, ApJ, 531, 846
Djorgovski S. G., Castro S. M., Stern D., Mahabal A., 2001, ApJ, 560, L5
Ellis R., Santos M., Kneib J., Kuijken K., 2001, ApJ, 560, L119
Ellison S. L., Songaila A., Schaye J., Pettini M., 2000, AJ, 120, 1175
Fan X. et al., 2000, AJ, 120, 1167
Fan X. et al., 2001a, AJ, 122, 2833
Fan X., Narayanan V. K., Strauss M. A., White R. L., Becker R. H., Pentericci L., Rix H.-W., 2001b, AJ, in press, astro-ph/0111184
Gnedin N., 2000, ApJ, 535, 530
Haiman Z., Madau P., Loeb A., 1999, ApJ, 514, 535
Heger A., Woosley S. E., 2002, ApJ, 567, 532
Leitherer C., Ferguson H. C., Heckman T. M., Lowenthal J. D., 1995, ApJ, 454, L19
Loeb A., 2001, ApJ, 555, L1
Loeb A., Rybicki G. B., 1999, ApJ, 524, 527
MacLow M.-M., Ferrara A., 1999, ApJ, 513, 142
Madau P., Rees M. J., 2000, ApJ, 542, L69
Madau P., Shull J. M., 1996, ApJ, 457, 551
Madau P., Haardt F., Rees M. J., 1999, ApJ, 514, 648
Madau P., Ferrara A., Rees M. J., 2001, ApJ, 554, 92
Miralda-Escudé J., 1998, ApJ, 501, 15
Miralda-Escudé J., Cen R., Ostriker J. P., Rauch M., 1996, ApJ, 471, 582
Miralda-Escudé J., Haehnelt M., Rees M. J., 2000, ApJ, 530, 1
Oh S. P., 2001, ApJ, 553, 25
Oh S. P., Nollett K. M., Madau P., Wasserburg G. J., 2001, ApJ, 562, L1
Osterbrock D. E., 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei. University Science Books, Mill Valley, p. 42

Pentericci L. et al., 2002, AJ, 123, 2151
Razoumov A. O., Norman M. L., Abel T., Scott D., 2002, ApJ, 572, 695
Schaye J., 2001, ApJ, 559, 507
Shaver P. A., Windhorst R. A., Madau P., de Bruyn A. G., 1999, A&A, 345, 380
Shull J. M., van Steenberg M. E., 1985, ApJ, 298, 268
Songaila A., 1997, ApJ, 490, L1
Songaila A., 2001, ApJ, 561, L153
Steidel C. C., Pettini M., Adelberger K. L., 2001, ApJ, 546, 665
Tozzi P., Madau P., Meiksin A., Rees M. J., 2001, ApJ, 528, 597
Venkatesan A., Giroux M. L., Shull J. M., 2001, ApJ, 563, 1

This paper has been typeset from a TEX/LATEX file prepared by the author.